16. CONTRIBUTIONS *to the* GLACIAL GEOLOGY *of* SPITSBERGEN. By E. J. GARWOOD, M.A., F.G.S., & J. W. GREGORY, D.Sc., F.G.S. (Read February 2nd, 1898.)

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I. INTRODUCTION.

ON June 17th, 1896, the tercentenary of the discovery of Spitsbergen by Barentz, we first sighted the western coast of the great island, the unknown interior of which Sir Martin Conway's expedition had been organized to explore. The sea was strewn with floes, which barred direct approach to the shore, and the incidents of the passage through the ice helped us to realize that we were 13° north of the Arctic Circle, far within the area which, according to a once popular theory, was formerly buried beneath a massive cap of ice. But the first near view of the land was calculated to destroy whatever faith we might have had in the former existence of a north polar ice-cap. For the sharp, serrated ridges of Mount Starashchin (see Pl. XIX, fig. 2) and Dodman Den, which guard the entrance to Ice Fiord, indicate that Western Spitsbergen has not at any recent time been wholly submerged beneath an ice-cap.[1] Confluent series of glaciers occur in Spitsbergen at the present day, and form the so-called 'inland ice-sheets.'[2] One such can be seen to the north of Ice Fiord, rising gradually from the shore to the sky-line; while on the plateau south of the fiord are smaller, disconnected glaciers. Hence, during the passage up Ice Fiord, between the great ice-sheet to the north and the scattered glaciers to the south, through the ice-floes among which the steamer carefully threaded its way, and past the huge piles of ice heaped along the shore, we were impressed by the fact that Spitsbergen is an exceptionally favourable locality for the study of glacial geology; for the three main ice-agents may be seen there working side by side.

The literature upon Spitsbergen is voluminous; but the main object of this paper is to record our actual observations upon the points which seem to us to bear especially on glacial problems. It is therefore unnecessary to refer at length to the previous literature on the glaciation of Spitsbergen. We need only point out that the first satisfactory descriptions of the Spitsbergen glaciers are those of Martins [3] and Durocher [4]; that reference to the work of the numerous Swedish expeditions and an account of the views of Baron von Nordenskiöld will be found in Leslie's [5] summary of that distinguished explorer's voyages; that many valuable observations as to the action of coast-ice have been recorded by Mr. James Lamont,[6] F.G.S., and Col. Feilden,[7] and that an admirable account of many of the western glaciers has been given by the late Gustav Nordenskiöld.[8] Mention must finally be made of the careful measurement of the rate of movement in a Spitsbergen glacier by MM. de Carfort & Lancelin,[9] and of the figures of the King's Bay glaciers published by Hamberg[1] in 1894. The last-named author first called attention to the three most striking characters of the Spitsbergen glaciers, namely:—the false-bedding and lamination of the ice, the irregular distribution of the intraglacial material, and the wall-like termination of the glaciers. Some of these features may be discerned in Mr. B. Leigh Smith's admirable photographs, of which no published account has been issued, although a set of them is available for reference in the Map-room of the Royal Geographical Society.

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[1] The same conclusion has been previously advanced for other Arctic areas, such as Alaska, North-eastern Labrador, Northern and Southern Greenland. We have noted Prof. Tarr's objection to this view; but his suggested explanation of the facts advanced by Chamberlin appears to us quite insufficient—in Spitsbergen at least. See R. S. Tarr, Bull. Geol. Soc. Amer. vol. viii (1897) pp. 252–256.

[2] It is well to explain here the sense in which we use the word 'ice-sheet': we mean simply a sheet of ice. Those ice-sheets, such as that of Greenland, which completely bury the interior of a country, and in which the ice itself forms the watershed, we refer to as 'ice-caps.'

[3] Ch. Martins, 'Observations sur les Glaciers du Spitzberg comparés à ceux de la Suisse et de la Norvège,' Voy. en Scandinavie, etc. sur la corvette la *Recherche*, Géogr. Physiq. vol. i (1845) pp. 138–192.

[4] J. Durocher, 'Sur les Glaciers du Spitzberg comparés à ceux des Alpes,' *op. cit.*, Géogr. Physiq. vol. i (1845) pp. 320–349.

[5] A. Leslie, 'The Arctic Voyages of Adolf Erik Nordenskiöld, 1858–1879,' London, 1879.

[6] Jas. Lamont, 'Notes about Spitzbergen in 1859,' Quart. Journ. Geol. Soc. vol. xvi (1860) pp. 428–444; 'Seasons with the Sea-Horses,' London, 1861.

[7] H. W. Feilden, 'A Subaqueous Moraine,' Glac. Mag. vol. ii (1894) pp. 1–5.

[8] G. Nordenskiöld, 'Redogörelse för den Svenska Expeditionen till Spitsbergen, 1890,' Bihang k. Svenska Vet. Akad. Handl. vol. xvii, pt. ii, no. 3 (1892), 93 pp., 6 pls. & map.

[9] R. de Carfort & Lancelin, 'Étude sur le Mouvement des Glaciers dans la Baie de la Recherche,' pt. vi of 'Voyage de la *Manche* à l'île de Jan Mayen et au Spitzberg,' Paris (1894), pp. 116–124, pl. xxi.

Nothing, however, had been done in Spitsbergen comparable to the masterly studies of the Greenland glaciers which we owe to Prof. Chamberlin[2] and his colleagues, to Drygalski,[3] and to the contributors to the 'Meddelelser om Grönland.' We had the opportunity of studying in Spitsbergen the same types of glacier-structure that have been so admirably described and so beautifully illustrated by Prof. Chamberlin, whose series of memoirs forms the most important contribution to glacial geology during recent years.

It is unnecessary to say much about the stratigraphical geology of Spitsbergen; but, as we are bound to refer to the possible analogy between the geographical structure of that country and of Greenland, a few lines on the subject may be conveniently inserted. Spitsbergen itself (excluding North-east Land and the islands adjacent thereto) consists of two parts. There is an extensive eastern plateau formed of Devonian, Carboniferous, Triassic, and Cretaceous strata, which are in the main horizontal, and are in places penetrated by intrusive igneous rocks; and there is a lofty western mountain-chain formed of pre-Devonian granites, gneisses, and schists, which are in places associated with uplifted members of the sedimentary series.

We are glad of this opportunity of thanking Sir Martin Conway, whose careful preparations ensured the success of the expedition, and whose keen scientific interests led him continually to alter his plans so as to give us the fullest possible opportunity for our work. It was, moreover, a great advantage for us to be able to discuss difficulties with a mountaineer and a geographer who has so intimate a knowledge of Alpine and Himalayan glaciers. References to the localities and an account of the conditions under which our work was done will be found in Sir Martin Conway's book.[4]

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[1] Axel Hamberg, 'En Resa till Norra Ishafvet Sommaren 1892,' Ymer, vol. xiv (1894) pp. 25–61 & pl. i.

[2] T. C. Chamberlin, 'Glacial Studies in Greenland,' pts. i–x, Journ. Geol. (1894–97): pt. i, *op. cit.* vol. ii (1894) pp. 649–666; pt. ii, *op. cit.* (1894) pp. 768–788; pt. iii, *op. cit.* vol. iii (1895) pp. 61–69; pt. iv, *ibid.* pp. 197–218; pt. v, *ibid.* pp. 469–480; pt. vi, *ibid.* pp. 565–582; pt. vii, *ibid.* pp. 668–682; pt. viii, *ibid.* pp. 833–843; pt. ix, *op. cit.* vol. iv (1896) pp. 582–592; pt. x, *op. cit.* vol. v (1897) pp 229–240.

[3] E. von Drygalski, 'Grönlands Gletscher und Inlandeis,' Zeitschr. Ges. Erdk. Berlin, vol. xxvii (1892) pp. 1–62.

[4] 'The First Crossing of Spitsbergen,' London, 1897.

II. The Glaciers and their Action.

Precipitation in Spitsbergen is probably greatest along the western mountain-chain, for the winds from the south-west have crossed the comparatively warm waters carried northward by the Gulf Stream, and thus arrive laden with moisture. The snow that falls on the seaward face of the mountain-range has a ready escape down the steep slope to the sea; but, although the eastern plateau is intersected in every direction by deep valleys and branching fiords, the snow that falls on it has no such easy outlet: the snow therefore accumulates, until it forms either glaciers of the 'Piedmont' type or 'inland ice-sheets.'

The extent of the ice in Spitsbergen has been exaggerated: it has been stated, for example, that 'the interior of Spitsbergen at presents consists of an immense ice-plateau, from 1500 to 2500 feet in height, which has its issue into the sea by means of the glaciers, which everywhere on the coasts protrude into the sea.' It had, however, been proved by the Swedish expeditions, and especially by that under Prof. Nathorst & Baron de Geer in 1882, that some parts of the interior are free from ice. Belts of land break up the inland ice into three main sheets, as was shown very clearly by Lieut. Byström's map,[1] issued in 1896. We saw but little of these great ice-sheets, as we made no attempt to cross them. For, though they are of great interest from their probable resemblance to the ice-sheets that once covered some parts of the British Isles, yet their geological action can be better studied upon their margins than upon their surface; in a march across them probably little could be seen of the processes that take place within or below them.

In addition to these 'inland ice-sheets' there are in Spitsbergen glaciers of the ordinary Alpine type. They agree with those of Switzerland in most respects. They flow from high collecting-grounds until they melt away or are otherwise destroyed. They carry down upon their surface lateral and median moraines, and their ends are often surrounded by terminal moraines. But two differences between the glaciers of Switzerland and Spitsbergen were soon apparent. The former are the outlets of extensive snow-fields, and the material of which they consist passes from snow into ice through the stage of névé. But many of the Spitsbergen glaciers do not drain snow-fields, and their material passes directly into the condition of névé-ice and glacier-ice. Thus, at the head of nearly every glacier-pass that we crossed (for example, Fox Pass, Bolter Pass, Flower Pass), we found no true névé or gathering-ground of snow. In some cases such glacier-ice may have been formed by avalanches; but at least in one case this explanation is inadmissible, and we were forced to the conclusion that under Arctic conditions snow may be converted into ice without pressure, and that the existence of glaciers does not necessarily postulate the existence of great snow-fields.

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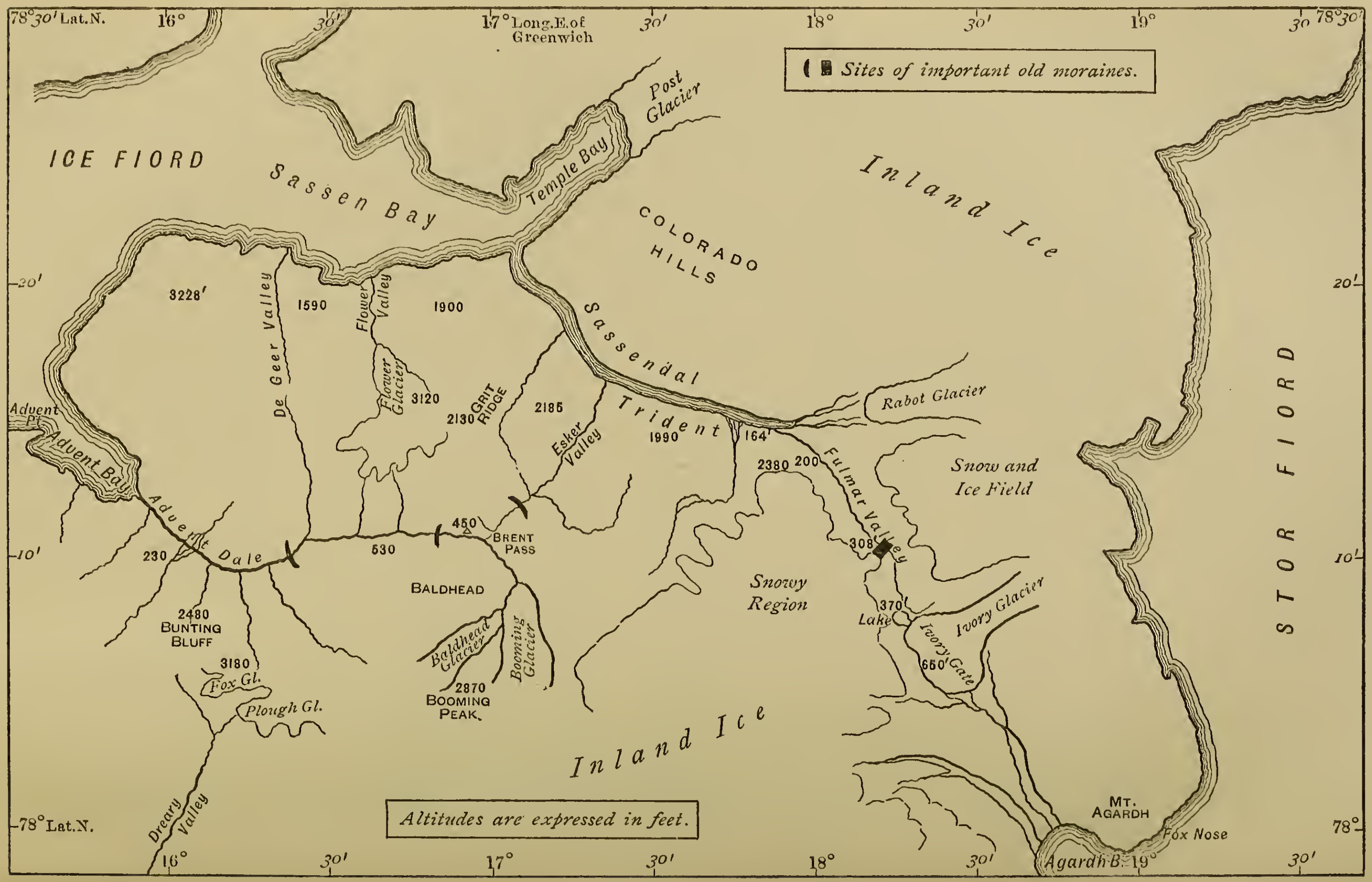
[1] H. Byström, 'Öfversiktskarta öfver Norra Polartrakterna,' Stockholm, 1896.

Fig. 1.—*Map of a portion of Spitsbergen, based on that published by Sir Martin Conway.*



But the most important difference between Arctic and Alpine glaciers is seen in the character of their respective terminal fronts. Most Swiss glaciers end with a tapering snout. Some of those in Spitsbergen (such as Flower Glacier, Baldhead Glacier, etc.) do the same; but the majority end in a vertical cliff of ice, of the type for which Lieut. Lockwood's apt name of 'Chinese wall'[1] is generally adopted. This name is appropriate owing to two characters: the face is vertical, and sometimes overhangs at the top like the machicolations of a mediæval fortress; secondly, the intraglacial material is arranged in lines like the layers of mortar in a wall.

The vertical faces of these Arctic glaciers have been suggested by Chamberlin[2] as largely due to the low angle at which the sun shines upon them. This no doubt assists in the formation of these Chinese walls,' for when the sun is low on the horizon it tends to cut the opposite face of the glacier backward by vertical ablation, instead of reducing its thickness by ablation over the whole upper surface. But the position of the sun is not the only factor, and we doubt whether it is a very important one, for the rays of the sun when it is near the horizon have comparatively little melting-power, compared with those which come from the zenith. Moreover, glaciers facing in the same direction and in the same neighbourhood sometimes end with tapering snouts, and sometimes with Chinese walls. (See Pl. XVII, fig. 1.)

Our first impression on seeing a glacier with a wall-termination was that this arrangement was due to the glacier being in a state of advance: and, so far as we could see, glaciers ending in snouts were either receding or stationary, while those with Chinese walls were always advancing.

The formation of the overhanging cornice appears to be due to the rapid forward movement of the uppermost layers of ice. This may be aided to some extent by the melting backward of the lower, dirt-bearing layers, owing to their greater absorption of heat; but in the case of at least some of the Spitsbergen glaciers, the influence of this factor must be quite insignificant.[3]

Glaciers with these Chinese walls are more instructive than those with snouts, and we therefore propose to describe one in some detail. The first view of such a glacier (see Pl. XIII, fig. 1) shows that it is composed of a lower part charged with débris, and an upper part in which the ice is pure and white. We almost instinctively proceeded at once to the foot of the ice-cliff to search for 'ground-moraine.' But the included material in the lower layers of the glacier, where not hidden by ice-talus, is so abundant that we found it in places impossible to draw any sharp line of separation between the glacier and the beds on which it rests. We found, in fact, a gradual passage from ice charged with morainic material into subglacial morainic material which has been saturated with water and frozen hard. We soon learnt that the idea of a 'ground-moraine' as a moraine formed beneath the sole of a glacier was not in accordance with the facts of Spitsbergen geology, for most of the glaciers there have no soles. But we learnt to regard the whole of the débris-bearing layers of the glacier as the representative of the ground-moraine, for they act as it was supposed to do.

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[1] A. W. Greeley, 'Three Years of Arctic Service,' vol. ii (1886) p. 34, & app. p. 28, figs. 3 & 4.

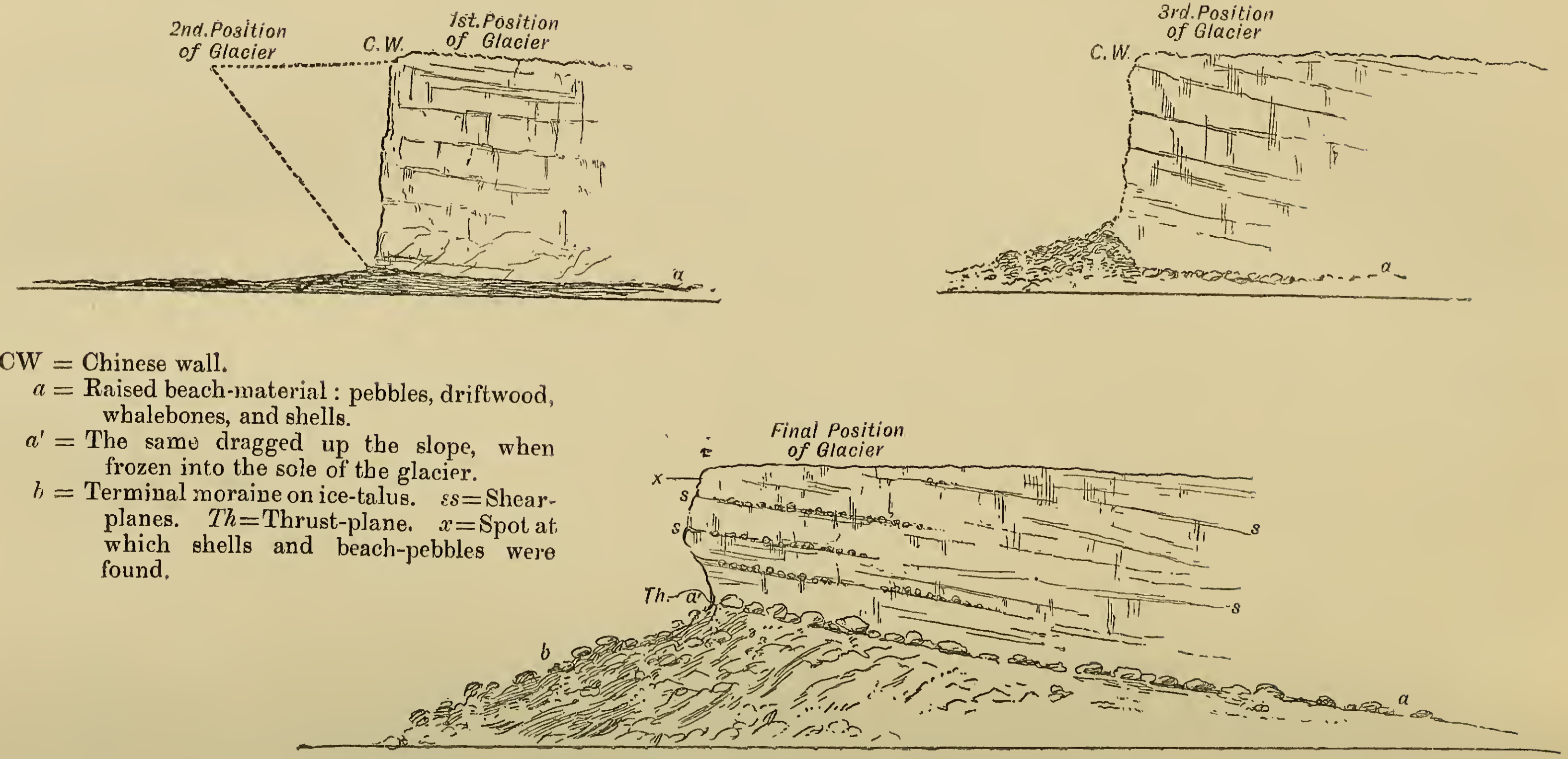
[2] T. C. Chamberlin, 'Glacial Studies in Greenland,' pt. vi, Journ. Geol. vol. iii (1895) p. 566.

[3] Its action has been invoked to help to explain vertical glacier-faces by Reid, and overhanging faces by Salisbury and Chamberlin. See H. F. Reid, 'The Mechanics of Glaciers,' Journ. Geol. vol. iv (1896) p. 926; R. D. Salisbury, 'Salient Points concerning the Glacial Geology of North Greenland,' Journ. Geol. vol. iv (1896) p. 782; and T. C. Chamberlin, 'Glacial Studies in Greenland,' pt. ix, Journ. Geol. vol. iv (1896) p. 591.

How the lower layer of the glacier becomes charged with débris was shown most clearly by sections at several of the glaciers which we examined, especially the Ivory Glacier, near Agardh Bay, and Booming Glacier at the head of Advent Dale. The photographs reproduced in Pl. XV, fig. 2, & Pl. XVI, figs. 1 & 2, as also the diagram on p. 204, illustrate the main stages in the process. As a glacier moves most quickly where it meets with least resistance, the upper layers flow forward more rapidly than those near the base. Accordingly, in a glacier which ends with a cliff-like face, the upper layers ride forward over those below, until they overhang as a projecting cornice. As the cornice is pushed still farther forward, masses of it break away and fall to the foot of the cliff. There they accumulate as an ice-talus bank, which in time becomes so large as to check the advance of the lower layers of the glacier. If the talus-bank is too heavy to be pushed forward, the glacier is forced to ride over it. The ice, therefore, that was originally the uppermost layer of the glacier will then form the base, and be in turn forced to rise upward over later talus-banks that accumulate in front of it. As the process is continuous, the glacier advances by an 'overrolling' motion, the top layer falling to the bottom, and then working upward over other fallen masses.

The use of the word 'overrolling' is open to the objection that it suggests a very flexible or viscous character of the ice. Some of the most conspicuous features of these glaciers, such as their false-bedding, their differential flow, their apparently rapid advance and the readiness with which they expand into radial fans, suggest that their ice is far more mobile than that of the Swiss glaciers. But further acquaintance with the Spitsbergen glaciers led us to change this opinion, especially in the case of the débris-laden strata of ice. Closer examination showed that the false-bedding was due to shearing. As the glacier presses against its talus-bar, bands of ice are driven forward and ride across the lower layers along thrust-planes. Thus Pl. XVII, fig. 2, shows part of the upper face of Booming Glacier: the face is broken into two by a narrow platform. This ledge marks a band rich in débris, above which is one of the thrust-planes. Smaller shearing-planes occur all through the débris-laden portion of the glacier. Hence the mechanical movement of the lower sections of the glacier appears to be due to a

Fig. 2.—*Diagram showing the travel of material carried up an inclined plane, and ultimately deposited in front of a glacier.*



CW = Chinese wall.
a = Raised beach-material: pebbles, driftwood, whalebones, and shells.
a' = The same dragged up the slope, when frozen into the sole of the glacier.
b = Terminal moraine on ice-talus. *ss*=Shear-planes. *Th*=Thrust-plane. *x*=Spot at which shells and beach-pebbles were found.

series of shearing-planes, owing to the pressure of the ice behind, rather than to a viscous yielding or to the action of continuous fracture and regelation.

The overrolling advance of the glaciers affords a simple explanation of the origin of the débris-bands and intraglacial material with which the lower part of the glacier is so richly charged. Let us consider the case of a glacier passing over loose materials, such as a raised beach. The ice-blocks which form the talus are generally irregular in shape, and as they fall with some force their projecting corners are driven into the ground. The blocks are further hammered in by the fall of others upon them. When the glacier flows over the talus, the latter is probably first crushed and then re-solidified, during which some of the underlying earth must get frozen in with the ice. When this basal layer of ice works upward, it carries with it the material which it has picked up from the valley-floor. This process being continually repeated, the whole of the lower part of the glacier becomes charged with débris, which, if no other factor came into play, would at length be distributed in layers throughout the whole thickness of the glacier.

Such débris-bands have been described by Chamberlin from the glaciers of Northern Greenland; he, however, records them only from quite the lower part of the glacier. His observations agree with the view that has been often expressed, to the effect that the intraglacial drift of the ice-sheets of North America and North-western Europe was entirely limited to the basal layers. In some of the Spitsbergen glaciers, however, the intraglacial material, though most abundant in the lower part, is scattered throughout nearly the whole thickness, as in the Plough Glacier (Pl. XIII, fig. 1).

That the intraglacial drift is picked up from off the valley-floor and raised through the glacier was shown in one case by the nature of the material. The terminal lobe of the Ivory Glacier, which occupies part of Agardh Dale, flows over a plain of recently-upraised sea-floor, whose surface is thickly covered with water-worn pebbles and mud. Scattered throughout this deposit occur numerous shells, with driftwood and fragments of whalebone. We found fragments of the shells of *Saxicava rugosa*, *Mya truncata*, etc. in some abundance in the lower débris-bands of the glacier, and on the lower slopes of the terminal moraine; at higher levels, the shells are scarcer and more fragmentary. We found one fragment at the height of 400 feet, and that we did not find any still higher was probably due to the hurried nature of our search.

It may be suggested that these marine remains found in the moraine were derived from some old raised beach, which is situated at a level higher than that at which we found them. The highest raised beach that we could find in the traverse from Sassen Bay to Agardh Bay was not more than 200 feet above sea-level. We found no trace of any raised beach in the upper Fulmar Valley between the great morainic bar and the northern face of the Ivory Glacier. In the lower Fulmar Valley we found traces of raised beaches, but we doubt whether they reached the 300-foot level (see fig. 3, p. 206). The highest terraces that we could see on the sides of

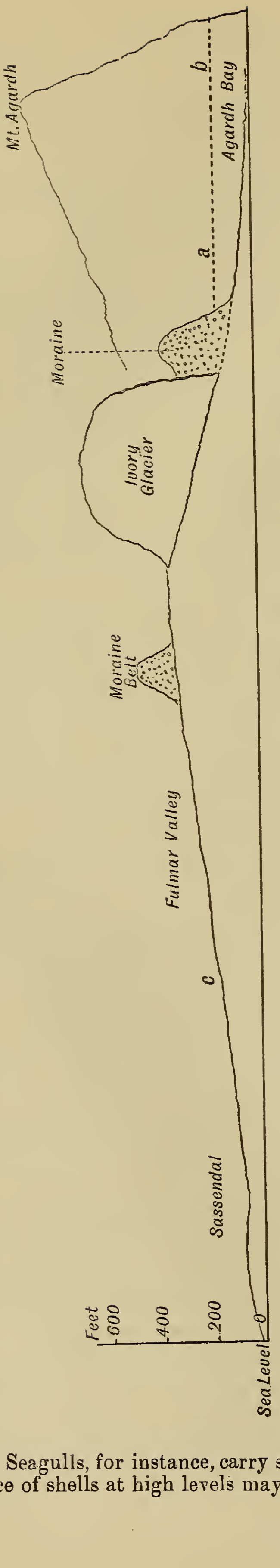


Fig. 3.—*Section along the valley-floor from Sassendal to Agardh Bay.*

a–b = Approximate position of the highest raised beach in Agardh Bay.
c = do. of the highest beach-deposits in Sassendal.

Agardh Dale were certainly at a lower level than this; hence the shell-fragments occur at least 200 feet above any raised beach in the immediate neighbourhood. If the case rested on shell-fragments alone, the negative evidence would perhaps be inconclusive[1]; but the bulk of the moraine and the intraglacial material consists of waterworn pebbles and similar beach-material; among it we found, moreover, fragments of whalebones and driftwood. Raised beaches on the flanks of a valley would not have yielded sufficient material: the quantity is so enormous that it can have come only from some thick deposit, such as that formed in an up-silted bay. We could see no sign of any high-level beach-deposits whence the material could have been derived.

Considering, therefore, that the glacier certainly passes over beach-material, which it can be almost seen to enclose and elevate, we have no hesitation in attributing the present elevation of the shells to uplift by the glacier rather than to derivation from hypothetical deposits, the existence of which at the height required is improbable.

The upward flow of layers of glacier-ice was, however, proved in another way. Fig. 4 is a diagrammatic sketch of part of the eastern side of Booming Glacier, about ½ mile from its lower end. A seam of ice-breccia is seen to run obliquely across the section from top to bottom. If the glacier were flowing like an ordinary stream in an unobstructed channel, then this band of ice-breccia would cut right across the lines of flow. The stratification of the glacier at this point is clearly due to deposition, for the breccia has certainly not been formed by crushing along a plane within the glacier. The section shows therefore that the movement of the ice is oblique to the main axis of the glacier.

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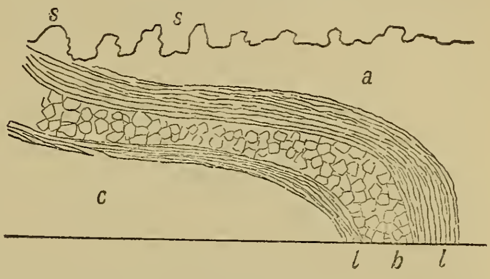
[1] Seagulls, for instance, carry shells to their nests. Some cases of the occurrence of shells at high levels may be thus explained.

Fig. 4.—*Part of the eastern side of Booming Glacier.*



a=Ordinary granular ice.
b=Ice-breccia. *l*=Laminated ice.
c=Black massive ice. *s*=Séracs.

The differential movement in the Spitsbergen glaciers that we have been previously considering must be too limited in lateral range to account for any commingling of boulders from different sources. The differential movements caused by the deformation of the ice during its flow may be considerable in amount both vertically and longitudinally. But the lateral movements thus produced must be small. Glacial geologists long ago explained[1] the intermixture of boulders from various localities by the assumption that the ice at different levels below the same point on a glacier may be moving in different directions. That this supposed action does take place, and on a large scale, is, we think, proved by the following case. It is further of interest as an illustration of the spasmodic nature of the alternate advance and retreat of Spitsbergen glaciers.

The terminal face of Booming Glacier is at present advancing, whereas nearer its source the glacier is diminishing, apparently owing to a diminution in the snowfall at its head (see Pls. XVIII & XIX). The upper surface of the glacier is saucer-shaped, being higher at the margin than in the middle, so that it appears as though the ice, in flowing forward, were climbing upward. But we doubt whether this be the true explanation: it seems more probable that the central depression has been formed by subsidence, owing to the melting and solution of the lower layers of the ice. It is, of course, possible that the ice has actually been forced to rise up a slope of moraine, much as water is heaped up round the margin of a lock into which a powerful current is flowing. Chamberlin[2] has described cases among the North Greenland glaciers in which the downward slope is not uniform in direction, but is interrupted by depressions sometimes so great as to lead to a reversal in the flow of the supraglacial streams. These reversed slopes, however, compared with the ice-fields on which they occur, form only minor undulations, and the glacier may be riding over obstructions in the manner of the car of a switchback. But the upward slope on the margin of Booming Glacier is so great, in proportion to the length of that glacier, that we cannot reconcile the ascent of the ice with any theory of glacial flow. We are therefore driven to regard the depression in the middle of this glacier as due to recent shrinkage. Some of the tributaries to Booming Glacier have not been affected by the diminished snowfall which has led to the decrease of the main stream. Thus a glacier that flows down from the Baldhead has continued to advance, and is now spreading out over the ice-stream by which it was once dammed back and absorbed. A point in the middle of Booming Glacier, which at one time only received material from the sources of the main stream, now receives a supply from the source of the tributary. If Booming Glacier increases in size, it will again block the lateral glacier, and all the morainic material along its middle line will come from the peaks at its head. Hence, in the deposits of the glacier there would be a layer with boulders from the west, interstratified between layers in which all the material came from the south.

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[1] See, for example, J. G. Goodchild, 'The Glacial Phenomena of the Eden Valley,' Quart. Journ. Geol. Soc. vol. xxxi (1875) p. 69.

[2] T. C. Chamberlin, 'Glacial Studies in Greenland,' pt. x, Journ. Geol. vol. v (1897) p. 231.

III. The Deposits of the Glaciers.

The deposits of the Spitsbergen glaciers may be conveniently divided into four groups:—

(1) Normal moraines of the Swiss type.
(2) Moraines formed of intraglacial material.
(3) Moraines formed of redeposited beach-material.
(4) Glacial gravels.

(1) Normal Moraines of the Swiss type.

This division includes moraines formed of material that has been carried on the surface of glaciers. The boulders of these supraglacial moraines are mainly angular, irregular, and unscratched; they generally occur in ill-assorted material, which is coarse and granular, and in which arenaceous material predominates. A few rounded and some scratched boulders occur, but the proportion is not greater than in an ordinary Swiss moraine.

Moraines of this character are common in the Spitsbergen uplands. As examples, we may cite some of those on the flanks of Booming Glacier, one in Esker Valley on the north-eastern side of Brent Pass, and the moraines at the northern foot of Mount Nordenskiöld.

The moraines agree in their general characters with those of existing Swiss glaciers, and there is accordingly no need to describe them.

We may refer, however, to a case of the formation of crescentic moraines by the Grit Ridge Glacier. A lateral glacier in the valley is depositing a series of crescentic terminal moraines on the surface of the main glacier. These moraines are being carried forward by the main stream, and when that melts they will be deposited along one side of its valley. The direction of the moraines of this tributary will be different from that of the deposits of the main glacier; and the moraines will be probably deposited at the foot of the left bank of the valley, some distance below the tributary at the mouth of which they were formed. The occurrence of small terminal moraines along the sides of a valley has been recorded in England and Greenland, and variously explained.

(2) Moraines formed of Intraglacial Material

are more important and interesting. The main characters of these deposits are that the materials are subangular and rounded; while scratched and polished pebbles and boulders are abundant. The coarser constituents are scattered through a fine-grained matrix, which is often well laminated, and may be false-bedded: this matrix is frequently argillaceous. Lenticular masses of clay in sand, or of sand in clay, are often present. The moraine may be either well stratified, or there may not be a trace of stratification in it.

The most striking difference between moraines of this group and those of the Swiss type is the much greater percentage of rounded and striated boulders. Thus, in the supraglacially-formed moraines of Booming Glacier, it often needed some search to find a striated boulder. The following list shows the character of the intraglacial material, represented by a small heap lying in front of the face of Booming Glacier:—

	Boulders.	Pebbles.
Rounded and striated...........................	27	6
Angular and subangular and striated ...	7	0
Angular, but not striated	12	10
Rounded, but not striated	3	3

The matrix was a tough clay. The proportion of pebbles was smaller than usual, for in some heaps they were more numerous than the boulders.

Moraines of intraglacial material are common in Spitsbergen around existing glaciers. They often form the basis of old moraines, the surfaces of which are covered by a layer of supraglacial morainic material. Our interest in these moraines was at once roused by their remarkable resemblance in composition to Boulder Clay. On the broad plain at the foot of Booming Glacier we found some square miles of a tough mud containing boulders and pebbles; it only needed to be dried and hardened in order to form an ideal Boulder Clay. Clearly this deposit had been laid down by land-ice, but not as a tip-heap at the end of a glacier. As the glacier gradually melted away, the materials scattered through it were deposited upon the valley-floor. Sections cut by streams through the deposits showed them to be sometimes laminated with remarkable regularity, forming clays of the type named by Goodchild 'gutta-percha clays.'

These deposits are not always regularly stratified, for they may be laid down in contorted masses. An instance of the formation of such contorted drifts was afforded by the Reiper Glacier, in which the basal layers of ice and the débris-bands were contorted by lateral pressure. On the melting of the ice, its included material is evidently dropped into false-bedded and contorted layers.

(3) Moraines formed of redeposited Beach-material

occurred in most of the principal valleys at the point where the glaciers had at one time entered the sea. There is one in Advent Dale, below the junction with De Geer Valley. But the moraine of this group to which we devoted the most careful examination is situated along the south-eastern face of Ivory Glacier. That moraine forms a series of conical hills of gravel, composed almost entirely of pebbles and sand; a few boulders occurred in it, and there were numerous broken shells, blocks of driftwood, and fragments of whalebones. As a rule the deposit was unstratified, but in places the streams that flowed from the face of the glacier had re-sorted some of the material.

In this Ivory Glacier moraine, although most of the materials have come from shore-deposits, land-ice is alone responsible for their present arrangement. But where a glacier has reached the sea, water plays a more important part and the materials are stratified. At Cape Lyell there are the remains of an old moraine in which the materials are stratified and very false-bedded: the deposits appear to have been arranged by tidal action at the foot of the glacier. The well-developed stratification of the beds on the western side of the great moraine in Advent Dale was probably similarly produced.

Mr. Lamont[1] has described a moraine in Deeva Bay, and Col. Feilden another at the head of Green Harbour, both of which may belong to this group. Feilden calls the latter a 'subaqueous moraine,' and says 'I have no doubt that this moraine was formed under water.'[2] But in a second description of the moraine he adds that the beds do not show any sign of stratification;[3] and we must confess to a doubt, as to whether mixed materials can be deposited on a large scale in shallow water, and exposed to the strong tides of a Spitsbergen fiord, without showing some 'sign of stratification.'

(4) Glacial Gravels.

One of the most remarkable observations made by Nansen during his traverse of Greenland was the insignificant part which water appeared to play in the economy of the ice-sheet. He found no stream flowing over the surface of the ice, and accordingly scouted the idea that kames and eskers could have been formed in channels upon the surface of the ice-sheet. The observations of other explorers have, however, shown that the conditions of the ice-sheet at the time of Nansen's march must have been exceptional. Jensen, for example, has published views of streams flowing over the surface of the ice-cap.[1]

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[1] Jas. Lamont, 'Notes about Spitsbergen in 1859,' Quart. Journ. Geol. Soc. vol. xvi (1860) p. 431.

[2] H. W. Feilden, 'A Subaqueous Moraine,' Glac. Mag. vol. ii (1894) p. 4.

[3] *Id.*, 'Notes on the Glacial Geology of Arctic Europe & its Islands, Pt. II,' Quart. Journ. Geol. Soc. vol. lii (1896) p. 740.

We were not surprised therefore to find that the Spitsbergen glaciers are intersected by river-channels, sometimes so deep as to be impassable for the sledges, and that numerous streams discharge from the terminal face of the glaciers. The stream that we examined most carefully was one on Flower Glacier, the course of which we followed during an ascent of Mount Lusitania. The channels both of the stream and its tributaries were generally quite free of débris. In fact all the supraglacial streams flowed with such velocity that they kept their channels quite clear, except of an occasional boulder. Whether subglacial streams deposit débris along their courses we could not of course directly see. But their velocity, so far as could be judged from the behaviour of the streams at the mouths of their tunnels, is probably even greater than that of the superficial streams. The latter flow in open channels, whereas the subglacial streams are forced through pipes, the size of which is no doubt kept at the minimum by the weight of ice upon the roof. It is only natural, therefore, that the power of the subglacial currents should be great, and it is not likely that deposits would be formed beneath them.

We at least found no trace of gravel-deposits resembling eskers formed either in subglacial or supraglacial streams. The moraines of the Ivory Glacier were in places kame-like in form, but they were certainly not formed subglacially. On the plain at the foot of Booming Glacier is a small esker-like ridge, but it is very low, and there is no available evidence as to its formation.

We were, however, so fortunate as to find a fairly typical esker in a position which left no doubt as to its origin. It occurred along the floor of a valley which descended from Brent Pass to the Sassendal. The valley is marked on Sir Martin Conway's map as the Esker Valley (fig. 1, p. 201).

The esker is about ½ mile in length, and its course is slightly sinuous. It varies in width at the base from 15 to 40 yards. Its upper end is semi-cylindrical in transverse section, but at the north-eastern end its summit is flattened into a platform 25 yards wide. The summit of the esker is almost horizontal, but the height of the ridge gradually increases from 20 to 35 feet owing to the slope of the valley. The esker rises from a flat, which at the time of our visit was ice-covered; a stream flowed across the plain on each side of the esker. Beyond the flat a terrace of gravel, similar to that which forms the esker, runs along each side of the valley at the same height. (See fig. 5.)

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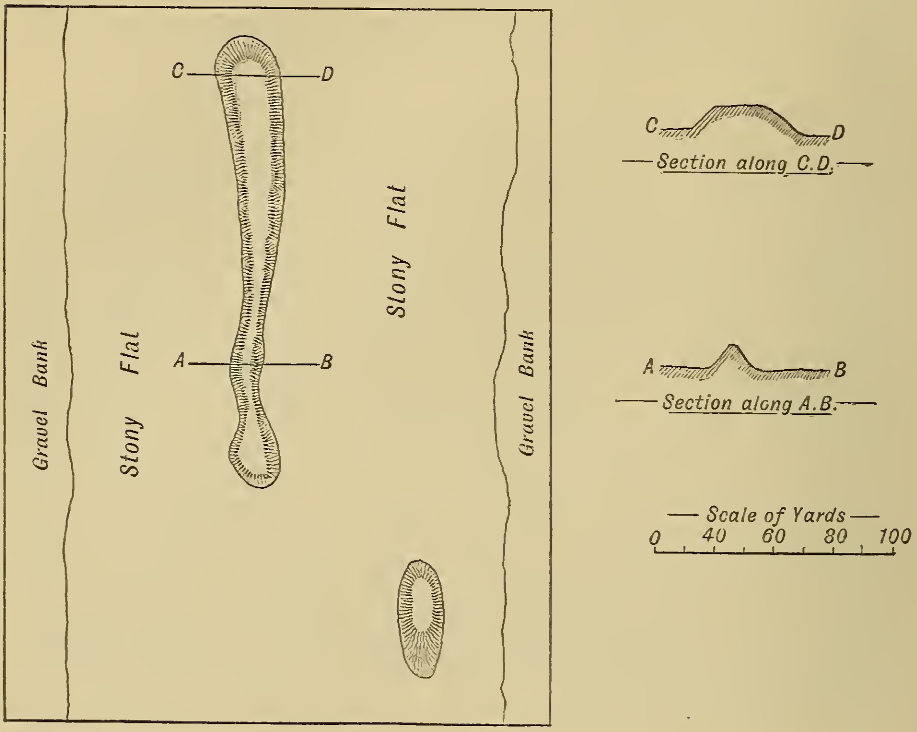
[1] J. A. D. Jensen, 'Expeditionen til Syd Grönland i 1878,' Medd. om Grönl. vol. i (1879) p. 61 & pl. iii.

Fig. 5.—*Sketch-plan and sections of the esker-like gravel-ridge.*



An examination of the valley in which this interesting gravel-ridge occurs leaves no doubt as to its mode of origin. At one time the mouth of the valley was blocked by a ridge of Carboniferous cherts which converted the middle part of the valley into a lake-basin. The streams filled this basin with gravel washed from the great terminal moraine in the upper part of the valley. Later on, the Esker Valley river cut through the chert-bar, and then the streams began the erosion of the gravel-plain. The esker has been left in the angle between the stream which comes from Brent Pass and a tributary which drains the southern slope of the Trident.

This explanation, of course, does not apply to all eskers. The reasons given by Prof. Sollas[1] for rejecting this origin of Irish eskers are conclusive for most cases. But, as Mr. J. B. Woodworth[2] reminds us, 'the term esker is applied in common usage to deposits having at least slightly different modes of origin,' and 'each esker should be diagnosed on its own merits.'

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[1] W. J. Sollas, 'A Map to show the Distribution of Eskers in Ireland,' Sci. Trans. R. Dubl. Soc. ser. 2, vol. v (1896) p. 786.

[2] J. B. Woodworth, 'Some Typical Eskers of Southern New England,' Proc. Boston Soc. Nat. Hist. vol. xxvi (1894) p. 219.

IV. Marine Ice and its Action.

Spitsbergen offers exceptional opportunities for the study of the geological action of marine ice, owing to its extensive shore-lines, its deep fiords, its numerous exposed islets, the powerful currents in the surrounding seas, and the rapid elevation which the land has recently undergone. Nevertheless, the results of the undoubted agency of marine ice are not very conspicuous.

The direct geological action of sea-ice is, so far as we could learn, of four kinds:—

(1) The transportation of material.
(2) The contortion of shore-deposits.
(3) The formation of small ridges and boulder-terraces above sea-level.
(4) The striation, rounding, and furrowing of rocks.

(1) The Transportation of Material.

The three main types of sea-ice may all act as transporting agents. Many of the blocks that floated down Ice Fiord were black with moraine-matter, with which they had been charged when part of a glacier. The ice-floes formed by the freezing of sea-water, though at first quite pure, are driven ashore by wind or tide, and there pick up a load of beach-material. In the case of the ice-foot the base is charged with fragments of the beach, while its upper surface is covered by the talus that falls upon it from the cliffs.

Ice of all three kinds is sometimes stranded, and when it melts away it deposits its load upon the shore. That this method of transportation of material must take place is obvious, and it has been repeatedly recorded. We need only remark that we saw many patches of boulders and pebbles, which were far distant from their place of origin. Along the shore of Ice Fiord, between Advent Bay and the head of Sassen Bay, there are boulders of gneiss from the north-west of Spitsbergen, and heaps of Old Red Sandstone from the head of North Fiord and Klaas Billen Bay.

(2) The Contortion of Shore-deposits.

Ever since the boat-voyage of Dease & Simpson in 1837, along the northern shores of British North America[1], it has been well known that the stranding of pack-ice has a very powerful action on shore-deposits.

The first result of this disturbance is the contortion of the layers of beach-material, though this cannot be seen clearly until streams have cut sections through the deposits. As one example, we may cite a case observed at Fox Point on Cape Lyell, on the southern shore of Bell Sound.

The disturbances produced by stranding floes are not limited to the spot actually struck by the ice, but frequently extend for some distance up the beach. The shore-deposits are often frozen hard, and weighted by a load of ice and snow; hence the pressure of the stranding ice results in a greater lateral movement of the materials than would happen if the beds were loose and incoherent, or were free to yield by increasing in thickness.

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[1] P. W. Dease & T. Simpson, 'An Account of [their] recent Arctic Discoveries,' Journ. R. Geogr. Soc. vol. viii (1838) p. 221.

A second result of the stranding of floating ice is the formation of bars at the entrance to bays. The bays often remain frozen over until much later in the season than the open fiords or sea. Thus Advent Bay was almost entirely covered by fast ice early in July, when Ice Fiord contained only loose drift-ice. Advent Bay is situated at an angle in Ice Fiord, where the shore, after a long east-and-west course, makes a bold sweep to the north-east. The prevailing winds blow up the fiord, and they accordingly drive the ice along the stretch of straight shore-line, and pack it into the angle by Advent Bay. As the ice grinds along the shore it pushes the beach-material eastward, until it has formed a bar which juts out for a third of the distance across the bay. The bar has been strengthened by the accumulation of river-borne sediment in the dead water behind it, and by the packing of shore-material by stranding ice in front. Most of Advent Point is now above sea-level, but its low, flat surface shows that it has been at one time cut down by marine denudation. At Lomme Bay is a similar bar, of which an admirable photograph has been taken by Mr. Leigh Smith; the bar in this case is narrower than that at Advent Bay, so that stranding ice can ride across it, and plane down the ridges formed whenever the bar is pinched by heavy pack-ice.

The height on the shore to which action of sea-ice extends is, however, comparatively small. We were unable during our short stay to determine the maximum height to which ice can rise; for on a coast undergoing such rapid elevation as that of Spitsbergen it is impossible to distinguish between the action of ice forced up from the sea at its present level and that of ice which grounded when the land was lower. The crews of the Norwegian sloops, whose experience of the Spitsbergen coasts has been gained in many seasons and under different conditions, all agreed that the coast-ice rarely rises more than about 40 feet above sea-level. Mr. Martin Ekroll, who wintered on the east coast of Spitsbergen and carefully observed glacial action, gave 60 feet as the highest level to which he had seen ice pushed above the sea.

(3) Shore-ridges and Boulder-terraces.

Series of raised beaches at different levels are common in Spitsbergen, and associated with these are two features which may be noticed, as due to the action of shore-ice.

Between the main raised beach-lines occur numerous small wavy ridges, which often resemble the ridges between plough-furrows. A few days' observation on shore supplied a simple explanation of their mode of origin. At the end of June the shore of Ice Fiord was bounded by a belt of fast ice; as it melted, a channel of water was formed between it and the shore. When the temperature fell to freezing-point, this water, being practically quite fresh, was frozen. Owing to the resistance of the ice-belt, the newly-formed ice could expand only on the landward side; as the young ice presses against the shore, it pushes the beach-material before it into ridges. These are often somewhat irregular in their course, for the water freezes into hexagonal masses, and the ridges necessarily acquire the angular course of the margin of the ice that forms them.

A second characteristic feature of a beach moulded by shore-ice is the occurrence of lines of large, rounded, or subangular stones, in form strikingly like those of the East Anglian Boulder Clay. They are pressed together so closely and regularly as in some cases to resemble a terrace of masonry or a pavement of cobbles. The first beaches of this type that we met with were at Cape Starashchin. The shore is steep, and is broken into a series of platforms; the faces of the platforms are almost entirely free from boulders, while the terraces between are often paved with closely-packed boulders. Subsequent observation and dredging between tide-lines showed that these peculiar congregations of boulders were due to stranding ice, which had pushed the boulders before it to just above sea-level, and left the beach between tide-lines quite clear.

A good illustration of similar boulder-terraces on Rolfsoe, near Hammerfest, is given in the atlas to the voyage of the *Recherche*.[1] Baron von Nordenskiöld[2] has described similar boulder-accumulations in Nova Zemlya; he calls them 'stone ramparts,' and gives the same explanation as that at which we had independently arrived. The 'boulder-pavements' on the shores of the American lakes, which have been admirably described and figured by Prof. J. W. Spencer,[3] may be mentioned in this connexion; but they are different both in aspect and origin.

These peculiar lines of boulders are probably not easily destroyed, and thus they may sometimes be useful as a test of shore-action. Campbell[4] has described a beach near Dunrobin in Sutherland, composed of 'terraced piles of boulders which do not seem to be moraines,' but which may be an example of this form of ice-action. Campbell himself suggested that it was probably due to the ice-foot.

(4) The Striation, Rounding, and Furrowing of Rocks.

We had few opportunities of observing the action of shore-ice on rocky shores, as our camps during the early period of our visit were on wide raised beaches. But that shore-ice can both scratch and polish rocks we had abundance of indirect proof. The same results are produced by land-ice, and we saw no means of discriminating between the striæ produced respectively by glaciers and floating ice. We were therefore interested to hear from Mr. Martin Ekroll that, in his opinion, furrows are formed only by the latter agent. The furrows he regards as always due to fragments of floes which have been thrown up on their sides; the whole weight of the slab of ice then presses directly upon the surface below. The edge of the ice becomes charged with rock-fragments from the beach, and as it is driven forward it cuts into the rock-surfaces like the edge of a file, instead of polishing them like its face.

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[1] 'Voyages en Scandinavie . . . . sur la corvette la *Recherche*,' Atlas géologique, pl. vii.

[2] A. E. Nordenskiöld, 'The Voyage of the *Vega* round Asia & Europe,' vol. i (1881) p. 188.

[3] J. W. Spencer, 'Ancient Shores, Boulder-pavements, & High-level Gravel-deposits in the Region of the Great Lakes,' Bull. Geol. Soc. Amer. vol. i (1890) pp. 71–86 & pl. i.

[4] J. F. Campbell, 'Frost and Fire,' vol. ii (1865) p. 155.

Mr. Lamont[1] has previously described a glacial furrow on one of the islands of Stor Fiord, and given good reasons for thinking that it was formed by floating ice; the furrow, however, in that case was not cut in solid rock.

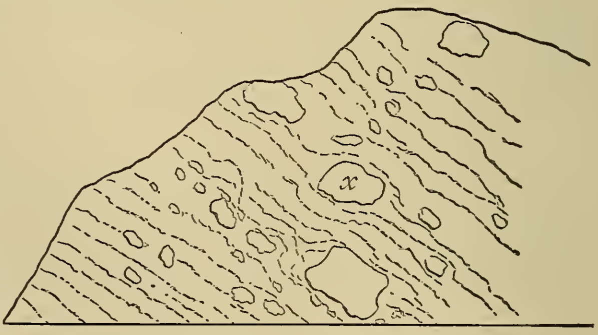
V. Traces of Former Glaciation.

The literature upon Spitsbergen abounds in references to the former greater extension of some of the existing glaciers. But there has been a complete agreement as to the absence of any signs of a pre-Pleistocene glaciation. Sedimentary rocks belonging to the pre-Devonian, Devonian, Carboniferous, Triassic, Jurassic, Cretaceous, and Palæogene systems are abundant; but, as Baron von Nordenskiöld tells us, 'at least we in vain, in the various rocks of that island, searched for stones furrowed by the action of ice, or boulders, or other beds resembling the glacial deposits of the present age.'

We were, however, so fortunate as to discover two cases of apparent glacial deposits in the Spitsbergen series. The oldest is a bed of a massive conglomerate at Fox Point, which belongs to the Hekla Hook series. The best section is exposed in a small headland, and shows some 50 feet thickness of the series.

The matrix is comparatively fine-grained, and has acquired by pressure an imperfect foliation. (See fig. 6.) Scattered through the groundmass are huge boulders, of which the largest was 5 feet high and 7 feet long. The boulders are roughly rounded, and the surfaces are sometimes marked by indefinite groovings, but we were unable to find any definite striæ. The boulders consist of a miscellaneous collection of granites and gneisses, none of which have at present any outcrop near the locality where the deposit occurs.

Fig. 6.—*Diagram of the Hekla Hook glacial beds, Bell Sound.*



x=Boulder 5 feet high and 7 feet long.

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[1] Jas. Lamont, 'Seasons with the Sea-Horses,' 1861, p. 204.

The matrix is often contorted, and the fine beds are crushed and bent as they pass round the huge boulders. This crushing and the imperfect cleavage are, no doubt, due to subsequent earth-movements. But the deposit is not a crush-breccia, and the boulders are foreign to the locality. The general aspect of the deposit is strikingly like that which a moraine would probably adopt if solidified, uptilted, and subjected to extreme pressure. The age of the deposit is probably the same as that of the old glacial conglomerate on the Varanger Fiord described by Reusch and Strahan.

On the northern face of Bunting Bluff, in beds which are of late Mesozoic or early Kainozoic age, one of us found another apparently glacial deposit. It contained huge boulders of granite and other rocks foreign to the locality; some of these showed scratches which are probably glacial in origin.

At the mouth of Bell Sound, we found another case of the occurrence of polished boulders scattered through a matrix of fine materials. This bed is Lower Kainozoic; but the boulders were all well rounded, and they were never more than a foot in diameter. The evidence in this case is less satisfactory, but the action of floating ice would afford the most ready explanation of the characters of the deposit.

VI. Some General Conclusions.

In the preceding pages we have tried to limit ourselves to a simple statement of facts, only classifying our observations and introducing such theoretical suggestions as to justify their record. We now propose to refer very briefly to the bearing of some of the facts on the problems of glacial geology.

(1) Land-ice *versus* Sea-ice.

In view of the long controversy between the advocates of land- and floating ice, we sought for some test by which to distinguish the action of these agents. But we could find no character by the use of which it would be possible to decide whether a given deposit had been formed by glaciers or by floating ice. Both forms of ice round rocks, cut striæ, and deposit heaps and ridges of contorted and false-bedded material. The mere presence of marine shells is useless, for they are transported and uplifted like any other material with which a glacier has to deal.

True boulder-paved terraces and shore-ridges can perhaps be formed only by shore-ice; but recognition of the latter would be impossible after denudation of the deposits had taken place; and cases have been described in which the action of a glacier on a moraine crowded with boulders has formed a pavement closely resembling those of the boulder-paved terraces.[1]

We found nothing being formed that would consolidate into a good Boulder Clay like those of Northern England except on land.

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[1] W. Upham, 'Irregularity of Distribution of the Englacial Drift,' Bull. Geol. Soc. Amer. vol. iii (1892) p. 136.

On the other hand, we found nothing among the morainic beds exactly like the Cromer Till and the Essex Boulder Clay. And given a supply of suitable materials, we see no impossibility in the formation in a quiet bay of a subaqueous deposit that would be indistinguishable from a boulder-clay.

The determination as to which of two types of ice has formed a particular deposit must therefore be left to the general probabilities of each case.

(2) The Transmarine Passage of Glaciers.

The rapidity with which glaciers are destroyed when they enter the sea seemed to us a feature of some importance in connexion with the suggested passage of an ice-sheet from Scandinavia into England. Hammer's[1] careful observations upon the Jakobshavn Glacier have given exact data as to the solution of glacier-ice by sea-water at low temperatures: he found that in the winter, when the sea-water was at a temperature below $-1°$ C., ice submerged beneath it diminished 200 times as quickly as when exposed to air of the same temperature. It is therefore not surprising that no case is known of the passage of a glacier across any belt of sea, as the old Scandinavian Glacier is assumed to have done.

It may be urged that an elevation of 250 feet would convert most of the North Sea into dry land; but the Norwegian Channel, the highest ridge across which lies 140 fathoms deep, would still be left. To drain it, an elevation of 1200 feet would be necessary. Even if this great rise had taken place, the channel would still serve as a serious obstacle to the passage of Scandinavian land-ice to the south-west; for, as Prof. Bonney[2] has pointed out in an unanswered enquiry in 'Nature,' the ice would tend to flow down the valley to the north.

The value of another objection to the theory was impressed upon us during the voyage along the Norwegian coast. Some of the Lofoten Islands and smaller islets to the south have unglaciated contours. Their jagged summits must have risen above the ice, like the nunataks on the borders of the Greenland ice-cap. In some places at least, the Scandinavian ice cannot therefore have extended much farther west than the present coast-line. This argument has been repeatedly advanced, and the evidence in its support has been clearly summarized by Sir H. H. Howorth.[3]

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[1] R. R. J. Hammer, 'Undersögelser ved Jakobshavns Isfjord og nærmeste Omegn i Vinteren 1879–1880,' Med. om Grönl. vol. iv (1883) pp. 34, 36, 64, & 265.

[2] T. G. Bonney, 'The Scandinavian Ice-sheet,' Nature, vol. xlix (1894) pp. 388–389.

[3] H. H. Howorth, 'The Glacial Nightmare & the Flood' (1893), vol. ii, pp. 703–710; 'On the Erratic Boulders & Foreign Stones of the Drift-deposits of Eastern England,' Geol. Mag. 1897, p. 155. For arguments in support of this view from a different line of consideration, see A. M. Hansen, 'The Origin of Lake-basins,' Nature, vol. xlix (1894) pp. 364–365.

(2) The Uphill Flow of Glaciers.

With regard to the cause of glacier-movements we have no fresh information. We found nothing inconsistent with the view that the flow is due to the action of gravity alone. The one apparent case of uphill advance with which we met may be as easily explained by local subsidence of the upper part of the glacier, owing to diminished snowfall, as by assigning climbing powers to the ice.

We do not deny that ice may sometimes surge upward when meeting obstacles in its path, a fact which probably explains such local variations in the level of a glacier as those described by Bonney[1] and Kendall[2] on the Gorner Glacier, by Chamberlin[3] and Wright[4] in Greenland, or the slight upbending of a thin glacier-snout over a moraine as recorded in the case of the Glacier de Zigiore Nuove by Sherwood.[5]

In the case of Greenland a great upward movement of ice is often assumed, on the ground that ice formed in the interior has to climb over a marginal mountain-chain. Thus Prof. Crosby[6] tells us that 'it is the general belief of geologists that if Greenland were divested of its ice-cap it would exhibit continental relief—elevated margins and a depressed interior.' This view of the geographical structure of Greenland appears improbable. Geologically Greenland is very similar to Spitsbergen. It very likely consists of a high plateau of sedimentary deposits supported on a great block of Archæan rocks, which are exposed round the margins. The hypothesis that there is a great depression in Central Greenland is not one upon which it is safe to base an argument.

(4) The Uplift of Material and Land-ice.

Nevertheless we found evidence, which we regard as conclusive, of the upraising of materials in glaciers. We can see no other satisfactory explanation of the occurrence of shells, whalebone-fragments, and driftwood in the Ivory Glacier moraines at an elevation greater than that of any raised beach known in the district. The bearing of this fact on the origin of the British high-level, shell-bearing drifts is obvious; but that question is also affected by the character of the earth-movements now taking place in Spitsbergen. The archipelago is now undergoing elevation, part of which at least must be positive, since the rate of movement varies horizontally. Thus the highest terraces we saw were those at Cape Starashchin, which slope downward towards the east. The terraces at the mouth of the Sassendal similarly descend to the south-east.

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[1] T. G. Bonney, 'Ice-blocks on a Moraine,' Nature, vol. xl (1889) p. 391.

[2] P. F. Kendall, 'Geological Observations upon some Alpine Glaciers,' Glac. Mag. vol. ii (1894) p. 121.

[3] T. C. Chamberlin, 'Glac. Stud. Greenland,' Journ. Geol. vol. v (1897) p. 231.

[4] G. F. Wright & W. Upham, 'Greenland Icefields,' 1896, p. 95.

[5] W. Sherwood, 'Glaciers of Val d'Hérens,' Nature, vol. xlvii (1892) p. 174.

[6] W. O. Crosby, 'Englacial Drift,' Amer. Geol. vol. xvii (1896) p. 225.

The elevation was most rapid on the south side of Ice Fiord, especially near its mouth, which is the line of greatest recession of ice. This coincidence is in harmony with Baron de Geer's[1] theory that depression and elevation have been often determined by the formation and disappearance of an ice-load.

Hence the weight of an ice-cap on Snowdon might itself lead to a depression of the area. This would lessen the height up which the Moel Tryfaen shells would have had to be uplifted by a glacier on the one theory. But, on the other hand, it would weaken the argument against the marine origin of the Moel Tryfaen sands based on the absence of evidence of submergence in other districts.

We therefore express no opinion as to the origin of these drifts, as we see no impossibility either in the local subsidence of the Snowdon area or in the uplift of the shells by land-ice.

(5) The Flow of Glaciers.

The internal processes in a glacier by which this uplift of material by ice is possible are intimately connected with the flow or advance of the glacier-ice. The mechanical processes are of three kinds.

There is first a simple flow like that of the Swiss glaciers, which takes place mainly in the upper layers which are free from intraglacial material. The ice in these upper layers appears more flexible than that of Switzerland, for the ice in the terminal cornice is often bent and curved. The greater flexibility may perhaps be due to the larger size of the glacier-grains, some of which are enormous. Some of them, in a block which had fallen from Booming Glacier, were 4 inches in diameter. These were much larger than any we had seen in Switzerland; and the biggest that we remember recorded thence were some found by Forel on the Aletsch Glacier, which were as much as 3 inches in diameter.

The nature of the ice-movement in the lower débris-laden portions of the glacier appeared to be very different from that of the upper part, for the ice behaves as if it were rigid and inflexible. The mere existence of vertical 'Chinese walls' shows that the ice is not capable of rapid change of shape. The advance of the ice is effected not by a flow like that of a viscous substance, but by a continual series of deformations, like a rock which is yielding under great strains. The ice is crushed and fractured, and successive slices are thrust forward along shearing-planes. A certain amount of melting and regelation also takes place, but these processes are much less important than in the case of Alpine glaciers or of the layers free from débris.

A third type of advance occurs in cases where the upper layers of the glacier move more rapidly than the lower; the glacier then progresses by an overrolling movement, banks of ice-talus being formed in front, which are subsequently overridden and again incorporated in the glacier.

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[1] G. de Geer, 'Quaternary Changes of Level in Scandinavia,' Bull. Geol. Soc. Amer. vol. iii (1892) p. 67; 'On Pleistocene Changes of Level in Eastern North America,' Proc. Bost. Soc. Nat. Hist. vol. xxv (1892) pp. 459, 473–474.

(6) The Transport of Material.

All the material carried by the glacier was either supraglacial or intraglacial. At least, we saw no sign of the dragging forward of subglacial moraine matter.

The supraglacial material is mostly angular, and agrees in general characters with that of Swiss supraglacial moraines. The main differences are that the erratics are usually smaller and the matrix more argillaceous, both of which are due to the nature of the rocks of the country and not to the glacial agencies.

The material carried intraglacially is very abundant, and forms the principal constituent of the Spitsbergen moraines. As is known to be the case in Greenland, and as is assumed to have been the case in the North American ice-sheet,[1] the material is mainly scattered through the lower layers of the ice; but there are cases in which it occurs throughout the whole thickness of the glacier. The material may be uniformly scattered through the ice, but it is generally collected along lines or into lenticular masses. It varies in amount from a thin dust, which slightly discolours the ice, to moraine-stuff which is simply held together by a small proportion of ice. We have referred to this material as intraglacial, instead of as 'englacial,' owing to the varying meaning given to the latter term. It was first proposed in 1883 by Chamberlin[2], who then used it in contradistinction to 'supraglacial' to include all 'the material embraced within the glacial ice.' Later on, however, Prof. Chamberlin limits the term to the material in the upper layers of the glacier. Thus he[3] remarks:—'The term englacial, as here used, does not include such materials as may be lodged in the basal stratum of the ice and brought down to the actual bottom by basal melting.' Hence, Prof. Chamberlin would exclude from the category of englacial drift by far the larger proportion of the material which we include in 'intraglacial' drift; for we include therein all materials included in the ice between the surface and sole of the glacier.

Other authors, such as Mr. Warren Upham[4]—the most energetic recent champion of the importance of 'englacial' drift,—use the term in a wider sense than either of the definitions just quoted. The difference in terminology no doubt increases the apparent difference of opinion as to the importance of intraglacially-carried material. Our observations certainly support the views of those who—like Mr. Goodchild, Mr. Upham, and Prof. Crosby—have attributed great importance to it. The distinction between supraglacial and intraglacial material is no doubt arbitrary, for débris may easily pass from one class to the other: the lowering of a glacier's surface by ablation must increase the supraglacial, at the expense of the intraglacial material.

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[1] W. Upham, 'Englacial Drift,' Amer. Geol. vol. xii (1893) pp. 38–39.

[2] T. C. Chamberlin, 'Preliminary Paper on the Terminal Moraine of the Second Glacial Epoch,' Ann. Rep. U.S. Geol. Surv. no. iii (1883) p. 297.

[3] T. C. Chamberlin, 'The Nature of the Englacial Drift of the Mississippi Basin,' Journ. Geol. vol. i (1893) p. 60.

[4] W. Upham, 'Irregularity of Distribution of the Englacial Drift,' Bull. Geol. Soc. Amer. vol. iii (1892) pp. 134–148.

The separation of intraglacial from subglacial material appears to us far less definite; and the six criteria suggested by Mr. Upham[1] are inapplicable in Spitsbergen. As we have previously remarked (p. 203), there is a very gradual passage from intraglacial to subglacial moraine-matter, although a sharp separation between them is often assumed, as, for example, by Upham.[2] The melting of an ice-sheet probably takes place on the lower as well as on the upper surface, and this may lead to some intraglacial material becoming subglacial. We agree, therefore, with Crosby[3] when he argues that there is 'no definite distinction between subglacial and englacial till, because, broadly speaking, it has all been englacial.'

We have especially quoted Mr. Upham as the latest champion of the importance of intraglacial material; but we have not forgotten that this view was upheld in this country many years previously by Mr. J. G. Goodchild[4] in his remarkable paper on 'The Glacial Phenomena of the Eden Valley and the Western part of the Yorkshire-Dale District.' We were constantly reminded during our study of the Spitsbergen glaciers of his protest against regarding Glacial Drifts as a ground-moraine, and of his explanation of their deposition by the quiet melting-away of an ice-sheet charged with rock-fragments. This paper was written 23 years ago; but the views expressed therein as to the transport and deposition of glacial beds agree more nearly with the glacial phenomena seen in Spitsbergen than those of any other contribution that we know to British glacial geology.

(7) Glacial Gravel-hills.

As in the case of recent observers in Greenland,[5] we saw no sign of the formation of eskers in either supraglacial or subglacial channels, or by streams flowing through ice-cañons. The only eskers that we found must have been formed by torrential action at some distance from the edge of the ice. None of the river-channels that we saw either in or on the ice contained much débris.

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[1] W. Upham, 'Criteria of Englacial & Subglacial Drift,' Amer. Geol. vol. viii (1891) p. 377.

[2] *Id.*, 'Englacial Drift,' Amer. Geol. vol. xii (1893) p. 38.

[3] W. O. Crosby, 'Englacial Drift,' Amer. Geol. vol. xvii (1896) p. 222.

[4] Quart. Journ. Geol. Soc. vol. xxxi (1875) pp. 55–99, pl. ii; and 'On Drift,' Geol. Mag. 1874, pp. 496–510. The former paper is reprinted, with additions and explanations, in Trans. Cumb. & Westmorl. Assoc. no. xii (1887) pp. 111–167.

[5] For example, R. D. Salisbury, 'Salient Points concerning the Glacial Geology of North Greenland,' Journ. Geol. vol. iv (1896) p. 809. An esker was described by Kornerup at Arsalik near Holstenborg, 'Geologiske Iagttagelser fra Vestkysten af Grönland (66° 55′–68° 15′ N. Br.),' Meddel. om Grönl. vol. ii (1881) pp. 192–193, 245.

In this connexion we may mention that a few drumlin-like mounds were met with, but not in such a position as to throw any further light on their formation.

(8) Differential Flow in Glaciers, and the Striation of Intraglacial Material.

Differential flow occurs in glaciers on a small scale, owing to the movement along shearing-planes; and one consequence of this appears to be a striation of the materials carried in the glacier. Prof. Russell[1] has recently pointed out that ice charged with débris must be more rigid than pure ice otherwise of the same character. When, therefore, a block composed of alternate layers of clean and débris-charged ice is subjected to pressure, it will yield more readily along the pure layers, and thus at once cause a differential flow. The pure layers are not absolutely free from débris, but usually contain some scattered pebbles, which will be dragged forward across the face of the débris-charged layer, causing mutual abrasion of the rock-fragments. Only by some such process can we account for the striation and rounding of the intraglacial material in some Spitsbergen glaciers.[2]

(9) The Evidence for Interglacial Periods.

The advance and retreat of the Spitsbergen glaciers are very irregular, and appear to be often due to quite local climatic changes. Ground from which ice has receded soon becomes covered with vegetation and inhabited by reindeer and foxes. The latter animals make caches of dead reindeer-meat as a supply for the winter, for we found heaps of bones which can have been collected only by foxes. The remains of plants and bones may thus readily become interstratified between beds of glacial drift by a further local advance of the ice.

We found moreover, in several places, a growth of plants on mud-hills covering sheets of 'fossil ice.' Owing to the protection of the overlying débris, the ice was melting very slowly; but as it dwindles in mass, numerous slips take place in the mud-hills, leading to the burial of the plants in a very admirable preserving medium. A future examination of these beds would probably show a remarkable interstratification of true glacial deposits with clays containing fossil plants and reindeer-bones.

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[1] J. C. Russell, 'The Influence of Débris on the Flow of Glaciers,' Journ. Geol. vol. iii (1895) p. 823.

[2] The striation of boulders carried intraglacially has been suggested by Kendall, Glac. Mag. vol. ii (1894) p. 45. But the angularity of most of the Swiss intraglacial débris is a further indication of the simpler character of the movements in the ice there. The fact has been used by Chamberlin, Bull. Geol. Soc. Amer. vol. v (1894) p. 85, as an argument against the uplift of material in glaciers.

(10) Glacial Erosion.

The Spitsbergen fiords have been often quoted as due to the erosive action of ice. But, as we hope to show in describing the structural geology of Spitsbergen, the fiords are the direct consequence of earth-movements. There is no evidence of the fiords having been even considerably enlarged by glacial action. So far as our observations extended, they support the views of those geologists—notably Prof. Bonney[1]—who have denied to glaciers more than a limited abrasive power.

(11) Glacial Periods as a Result of Epeirogenic Movements.

The theory that glacial periods have been formed as a consequence of epeirogenic uplifts receives no support from the glacial history of Spitsbergen. Throughout Kainozoic times Spitsbergen seems to have been part of a great land-area. In the Pleistocene period there came a depression, which appears to have coincided with the maximum glaciation of the country; for there is no trace of marine shells in the late Kainozoic, except after the time of the greatest extension of the glaciers. Moreover, the gradual elevation that is still taking place has been coincident with a general retreat of the glaciers; for the cases of local advance are not sufficient to outweigh the general evidence of a considerable recent decrease in the extent of the Spitsbergen ice-fields.

EXPLANATION OF PLATES XIII–XIX.

[All the Plates, except Pl. XV, fig. 1, & Pl. XIX, fig. 2, are reproduced, by kind permission of the Council of the Royal Geographical Society, from blocks in their possession.]

Plate XIII.

Fig. 1. Stratified morainic material in ice, Plough Glacier.
2. Contorted morainic material in ice of Reiper Glacier.

Plate XIV.

Fig. 1. Formation of crescentic moraines, Grit Ridge.
2. Terminal moraine, Ivory Glacier.

Plate XV.

Fig. 1. Moraine of Ivory Glacier.
2. Ivory Glacier, overriding terminal moraine.

Plate XVI.

Fig. 1. Further advance of Ivory Glacier, overriding terminal moraine.
2. Westernmost view of Ivory Glacier, ice advancing.

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[1] T. G. Bonney, 'Do Glaciers Excavate?' Geogr. Journ. vol. i (1893) pp. 481–499. For a recent summary of the literature on the subject, with a verdict adverse to the erosive theory, see G. E. Culver, 'The Erosive Action of Ice,' Trans. Wisc. Acad. Sci. vol. x (1895) pp. 339–366.

Plate XVII.

Fig. 1. Terminal fronts of Booming and Baldhead Glaciers.
2. Ice-talus formed from advancing upper layers, Booming Glacier.

Plate XVIII.

Fig. 1. View showing the raised edge of Booming Glacier.
2. Booming Glacier, looking up.

Plate XIX.

Fig. 1. Upper portion of Booming Glacier, showing the centre sagging away from the side of the valley.
2. View of Starashchin Ridge.

Discussion.

Sir Martin Conway called attention to the fact that the whole of the oval terminal dome of the Ivory Glacier—3 miles wide, 2 miles long, and about 400 feet thick—had been formed by the advance of the glacier from the neighbouring side-valley to the north since Von Heuglin's visit to Agardh Bay in 1870. The moraine-hills (220 feet above the level of the raised beach below) had therefore all been formed within that short interval. Referring to the advance of some of the Spitsbergen glaciers and the retreat of others, he pointed out that the glaciers which terminate with an ice-cliff in shallow bays, if they do not advance over the moraines deposited by them in the water, must cut themselves off from the water by a ring of terminal moraines. Instances of glaciers thus cut off, and of others thus advancing into the sea, were observed by the 1897 Expedition.

Prof. Bonney enquired whether Dr. Gregory had been able to establish any relation between the height to which a glacier had lifted material and that from which it had descended. He doubted whether much striation of pebbles would go on in the ice, but said that in Switzerland the number of striated pebbles increased as the moraine became more distant from the present end of the glacier. He also asked whether the beach-material was found to rise from the north towards the south, that is, in the direction of movement of the glacier. He thought the paper a most important one.

The Rev. Edwin Hill said that now for the first time we are given an intelligible theory of how moving ice may pick up materials and raise them high above its floor. The advance as described seemed analogous to that of a wave breaking on a beach, or a 'bore' advancing up a river. The uplifting action required a good deal of thought to attain a clear conception of its cause. The talus would doubtless be incorporated in the advancing mass and, he thought, might not much impede it, but the theory seemed complete, and independent of this. Such ice as that described neither ploughed nor eroded, contrary to common views, nor did he hear anything of intercrossing streams. A medial hollow might follow from sub-glacial melting, but what was the cause of advance if the rear were lower than the front? He had never listened with more interest to any paper.

Mr. P. F. KENDALL said that the paper would mark a distinct epoch in British glacial geology. Hitherto, one body of geologists had attributed the drift-deposits of Britain to the agency of land-ice, while another had invoked the agency of the sea. The latter had argued that glaciers cannot move uphill, that they cannot transport materials from lower to higher levels, that glaciers cannot gather up materials over which they are moving, and that even if they could pick up shells they would grind them to powder. The Authors have shown that the glaciers of Spitsbergen were actually doing each of these things. In his experience of the Alps he had never failed to find a profusion of scratched stones, and had observed in front of the Gorner Glacier actual striated pavements of well-glaciated boulders showing the 'forced arrangement' described by Hind. The ability of glaciers to striate englacial materials seemed to be indicated by the fact that, on the surface of the Findelen Glacier, scratched stones had been found (by himself and others) which were being liberated by melting from a gravel-filled crevasse. He had ascribed the striations to chafing in the crevasse by differential movements of the ice. The sharp splintered peaks referred to by the Authors need not imply that they had never been overridden by ice. Mr. G. H. Barton had described similar appearances in the Nugsuak peninsula, where, however, the occurrence of boulders and other indications showed that, though the rocks had been beneath the ice, rapid shattering by frost had destroyed the rounded glacial contours.

Mr. MARR also spoke.

Dr. J. W. GREGORY expressed gratitude for the reception of the paper. With regard to the points raised in the discussion, he said that Mr. Kendall's Swiss case of the striation of intraglacial material was noticed in the paper. They had considered the probable destruction of glaciated contours by frost, and Prof. Tarr's suggestions as to the preservation of jagged outlines under an ice-sheet; but they could not understand the sharp boundary between glaciated and non-glaciated slopes, except on the view that the latter had stood out above the ice. They had seen cases of differential movement in glaciers on a great scale, the ice at different levels travelling in different directions. The forward advance of the end of Booming Glacier in spite of the shrinking of the upper part is probably due simply to gravity, the glacier resting on a slope. He agreed with Mr. Hill that the retardation of the advance of the lower layers of the glacier by the talus-bar is unessential, nevertheless he thought that this retardation did take place.

Mr. GARWOOD, in reply to Prof. Bonney, pointed out that, owing to the radial spreading-out of the Ivory Glacier where it debouches onto the flat estuary in Agardh Bay, nothing but the terminal front is visible. In reply to Mr. Hill he observed that, although the Authors did not rely at all on the retardation of the lower layers of the ice by the accumulated talus for the formation of the vertical fronts, nevertheless they considered that this talus would probably assist in that formation.

With regard to the question of the excavating power of an advancing glacier, he thought that the very mode of advance of Arctic glaciers, as described in the paper, militated strongly against any appreciable action of this kind.

Commenting on the contrast between the angular contour of the higher ground and the curved slopes below, he pointed out that the extremely rapid weathering so clearly taking place at the present day must long since have removed most of the more obvious signs of glaciation, if these had been impressed on the high ground in former times.

He described a deposit of glaciated fragments of granite and diabase occurring on the plateau of Sticky Keep in the Sassendal, at a height of 1200 feet above the floor of the valley. These rocks must have been removed from the north, and have crossed the Sassendal, unless we assume the formation of the valley subsequently to the transport of the boulders. In his second visit to the island last summer, he had obtained evidence confirmatory of this, which he hoped to have the pleasure of laying before the Society at an early date.